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Title: Understanding blunt force trauma and violence in Neolithic Europe: The first experiments using a skin-skull-brain model and the Thames Beater

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Introduction

The presence of conflict-related blunt force cranial trauma in the British and European Neolithic has been firmly established in recent population studies (Schulting & Wysocki 2005: 107; Lawrence 2006: 53; Smith & Brickley 2007: 25; McKinley 2008: 477; Ahlström & Molnar 2012: 17; Schulting 2012: 223; Schulting & Fibiger 2012; Fibiger et al. 2013: 190; Meyer et al. 2015: 11217). Experimental studies into the mechanism of these injuries can greatly aid in understanding the variable cause and context of violence and therefore create more comprehensive interpretation of social interaction in prehistory (Schulting & Wysocki 2005: 107; Ahlström & Molnar 2012: 17; Schulting 2012: 228; Fibiger et al. 2013: 190; Wedel & Galloway, 2014: 73). Currently, very little research has been done to analyze any possible implements that may be responsible for cranial blunt force trauma in prehistory.

Experimental studies of blunt force trauma in other time periods have often utilized cadavers or animal substitutes when attempting to replicate intentional injuries, though both these mediums have major faults in accuracy or ethical issues (Corey et al. 2001: 104; Thali et al. 2002a: 199, 2002b: 178; Byard et al. 2007: 31; Raul et al. 2008: 359; Wedel & Galloway 2014: 140; Smith et al. 2015: 427). New methods utilizing synthetic 'skin-skull-brain' models have begun to emerge. These polyurethane human skull substitutes are uniform between individual samples and avoid the inaccuracies of animal substitutes and the legal and ethical issues of cadavers (Thali et al. 2002a: 195, 2002b: 178; Smith et al. 2015: 427).

This paper presents the results of the first use of skin-skull-brain models to investigate blunt force trauma causes in the Neolithic osteological record. A replica of the Thames Beater, a Neolithic wooden club, was able to produce fractures in synthetic skulls with remarkable comparisons to Neolithic skeletal remains from Asparn/Schletz, a massacre site in Austria (Teschler-Nicola 2012: 107), and demonstrates the suitability of this test method. This research opens up new and innovative avenues to explore the mechanisms and context of blunt force trauma in prehistory. This is essential for understanding its social and cultural context and meaning when considering both, remains from standard funerary contexts as well as the increasing number of remains from mass graves across Western and Central Europe (Orschiedt et al. 2003: 376; Schulting & Wysocki 2005: 107; Lawrence 2006: 47; Golitko & Keeley 2007: 333; Boulestin et al. 2009: 968; Fowler 2010: 1; Lorkiewicz 2011: 428; Ahlström & Molnar 2012: 17; Schulting 2012: 223; Schulting & Fibiger 2012: 2; Teschler-Nicola 2012: 101; Wahl & Trautmann 2012: 77; Fibiger et al. 2013: 191; Chenal et al. 2015: 1329; Meyer et al. 2015: 11217).

Blunt Force Trauma

Many mechanisms of injury can cause blunt force trauma and the limited way bone can react to an impact, either violent or accidental, can complicate the diagnosis of intentional and accidental mechanisms of injury (Alcantara et al. 1994: 521; Lovell 1997: 148; Raul et al. 2008: 359; Jacobsen et al. 2009: 2; Sharkey et al. 2012: 835; Wedel & Galloway 2014: 33). Cranial fractures are more often indicative of intentional violence than post-cranial trauma (Lovell 1997: 149; Chattopadhyay & Tripathi 2010: 102; Schulting 2012: 224; Fibiger et al. 2013: 191), however, certain fracture formations are often discounted as likely accidental trauma (Lovell 1997: 150; Ortnier 2003: 121; Freeman et al. 2014: 64).

Fracture formation from blunt force trauma to the cranium is influenced by the biomechanical properties of the skull (Lovell 1997: 155; Kasrai et al. 1999: 238; Wedel & Galloway 2014: 134; Carr et al. 2015: 508). Cranial sutures, the joints between the bones of the skull, are able to absorb force and can stop the progression of fractures across the surface of the cranium (Lovell 1997: 155; Wedel & Galloway 2014: 135). The skull is also buttressed with arched areas of thicker bone; fractures follow the path of least resistance and can be influenced by these patterns of strong and weak bone in the skull (Lovell 1997: 155; Kasrai et al. 1999: 238; Wedel & Galloway 2014: 141; Carr et al. 2015: 508).

Several types of fractures are formed from blunt force trauma as seen in Figure 1. Linear fractures are produced when a low velocity force is transmitted through a wide surface area; accidental injuries, like falls, are possible causes, leading linear fractures to be ruled out of many archaeological trauma studies that focus on violence (Lovell 1997: 150; Ortner 2003: 121; Schulting & Wysocki 2005: 110; Freeman et al. 2014: 64; Wedel & Galloway 2014: 137).

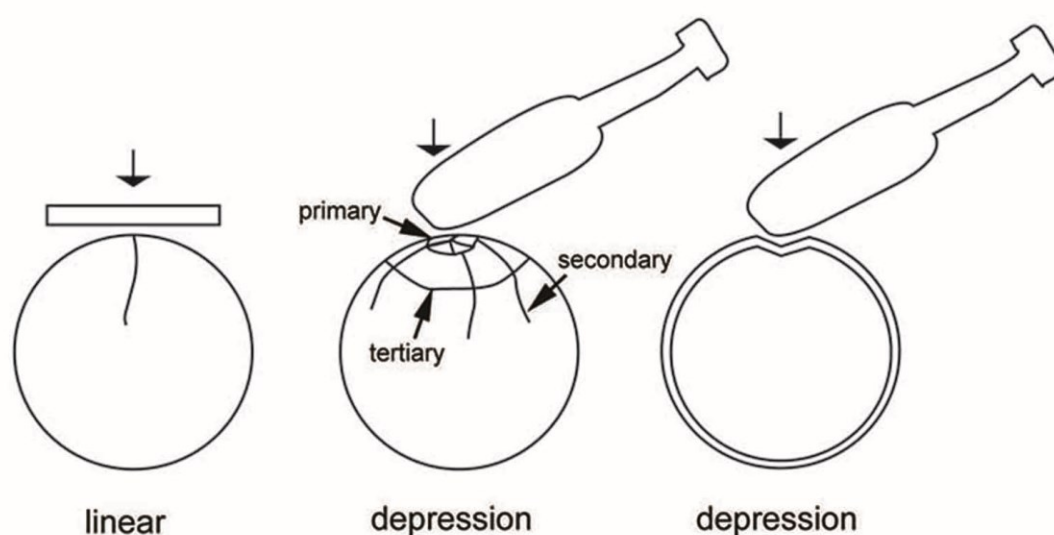


Figure 1: Diagram showing two types of blunt force cranial fracture. Left: a linear fracture. Centre: A depression fracture showing the primary impact site along with the secondary and tertiary fractures that may form on the surface of the cranium. Right: A depression fracture showing the in-bending created at the site of impact.

Archaeological studies instead focus on depression and penetrating blunt force fractures formed by a higher velocity and more concentrated force, which represent patterns strongly linked to armed blows (Oh 1983: 111; Lovell 1997: 154; Ortner 2003: 121; Schulting & Wysocki 2005: 110; Schulting 2012: 225; Wedel & Galloway 2014: 62). In-bending creates the beveled displaced bone at the impact site that along with secondary and tertiary fractures, are characteristic of depression fractures as seen in Figure 1 (Oh 1983: 116; Lovell 1997: 150; Ortner 2003: 121; Calc & Rogers 2007: 519; Wedel & Galloway 2014: 129; Smith et al. 2015: 428).

The Neolithic Osteological Record: Northwest Europe

Skeletal evidence presents the minimum number of injuries that occurred in a past population; assessments of the skeletal record of Britain and Europe during the

Neolithic have clearly established the presence of healed and peri-mortem intentional blunt force trauma (Schulting & Wysocki 2005: 107; Lawrence 2006: 56; Smith & Brickley 2007: 25; McKinley 2008: 477; Lorkiewicz 2011: 430; Ahlström & Molnar 2012: 17; Schulting 2012: 223; Fibiger et al. 2013: 190; Fibiger 2014; Chenal et al. 2015: 1313; Meyer et al. 2015: 11217). Healed trauma tends to be more prevalent in male skeletons, while peri-mortem trauma is more evenly distributed, which appears to suggest that males were the principle actors and instigators of violent interaction (Schulting & Wysocki 2005: 123; Ahlström & Molnar 2012: 17; Schulting 2012: 519; Fibiger et al. 2013: 190). The social and cultural context of this violence is still heavily debated, and a better understanding of the tools used for causing these injuries would greatly aid analysis.

The identification of tool typologies used as weapons can help establish if classes of tools were opportunistic weapons or designed solely for interpersonal violence, and if this varies based on the different evidence found in the osteological record (Schulting & Wysocki 2005: 107; Ahlström & Molnar 2012: 17; Schulting 2012: 228; Fibiger et al. 2013: 190). Establishing if different tools are used at massacre sites compared with standard funerary contexts can demonstrate possible similarities or discrepancies between the causes of the injuries. A fuller understanding of typologies of weapons used in blunt force injury is needed to make more substantiated interpretations about the osteological record.

Neolithic Weapons of Violence and the Thames Beater

Most of the Neolithic material record of Britain and North-Western Europe yields virtually no implements that can be unambiguously classified as weapons of violence (Christensen 2004: 139; Fowler 2010: 16; Fibiger et al. 2013: 191); instead potential weapon-tools including bows and arrows, axes, clubs and possible sling-type tools must be considered. Current studies have yet to establish which of these tools may have been used as blunt force weapons and mostly discuss the blunt force mechanism of injury alone, only speculating the particular implements used (Schulting & Wysocki 2005: 125; Smith & Brickley 2007: 25; Lorkiewicz 2011: 432; Ahlström & Molnar 2012: 27; Schulting 2012: 224; Schulting & Fibiger 2012: 2; Fibiger et al. 2013: 199; Meyer et al. 2015: 11220).

The Thames Beater is an alder club that was found in the Thames River near Chelsea and carbon dated to 4660 ± 50 BP (Beta-117088) (Webber & Ganiaris 2004: 126). It is one of a very small number of wooden clubs that survive from the Neolithic period in Britain (Webber & Ganiaris 2004: 126; Schulting & Wysocki 2005: 125). The original artifact is on exhibition in the Museum of London and a replica was produced by master carpenter David Lewis from Pelynt, Cornwall, based on the materials and dimensions of the original artifact (Figure 2). Both the Thames Beater and the replica are made of alder, a wood with an average density of $0.490\text{--}0.640\text{ g/cm}^3$ (Borůvka et al. 2015: 8284). The same raw material was used to create an accurate reproduction of the weight, strength and other physical properties of the original artifact when it was in use. The completed replica (Figure 3) measures 64.0cm in length (Table 1) and is comprised of a slightly angled 'blade', barrel, and pommel (Webber & Ganiaris 2004: 124).

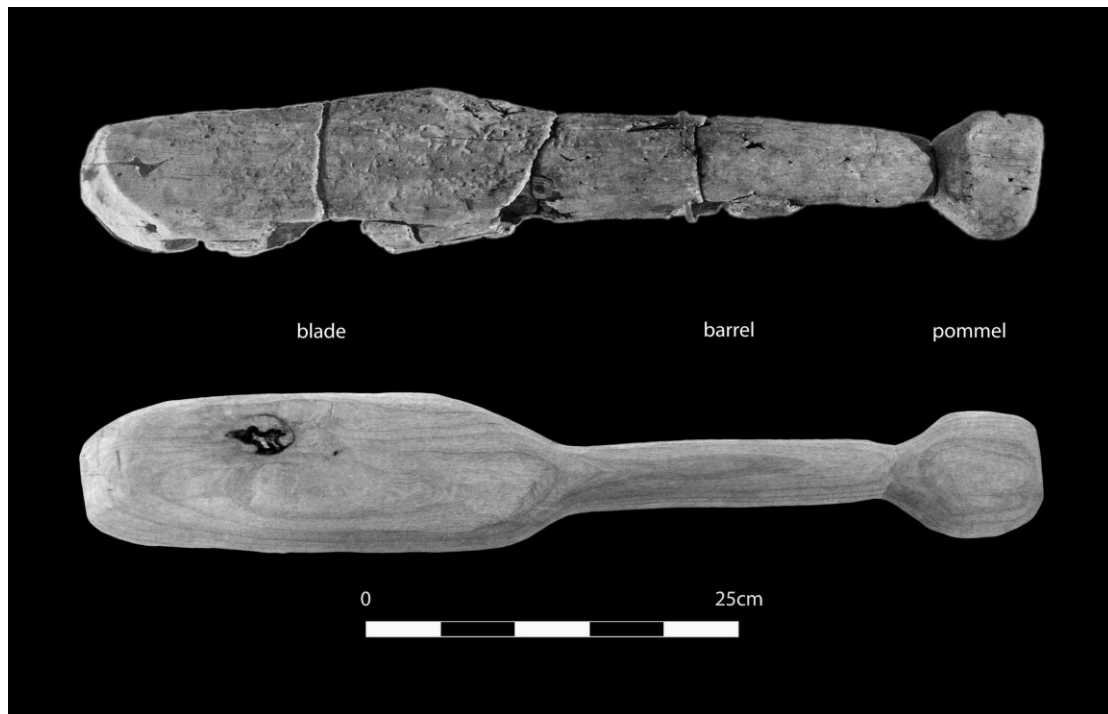


Figure 2: The Thames Beater (top) and replica club used for experimentation (bottom) showing the blade, barrel and pommel.

Table 1: Dimensions and weight of the Thames Beater replica

Measurement	cm
Maximum Length	64.80
Blade Length	32.40
Barrel Length	22.50
Pommel Length	9.90
Pommel Width	8.89
Pommel Thickness	5.83
Length of Blade Tip	5.75
Circumference of Barrel (pommel end)	13.60
Circumference of Barrel (mid point)	16.00
Circumference of Barrel (blade end)	15.40
Weight	1.17 kg

Wooden clubs are commonly used weapons in cultures across time and space (Walker 1989: 319; Alcantara et al. 1994: 522; Jurman & Bellifemine 1997: 48; Webber & Ganiaris 2004: 124; Lightbody & MacIver 2007: 112; Dujovny et al. 2009: 1005; Chattopadhyay & Tripathi 2010: 99). The low number of examples known from the Neolithic archaeological record reflects the poor preservation of organic materials from the period rather than their lack of use (Webber & Ganiaris 2004: 126; Schulting & Wysocki 2005: 125; Ahlström & Molnar 2012: 128). The study of clubs that do survive from the Neolithic can greatly aid in an understanding of their use as potential weapons.

Method

The synthetic bone spheres used for the skin-skull-brain models (Figure 3), were obtained from Synbone AG (Switzerland). The spheres consist of two hemispheres of specialized polyurethane material glued together and coated in an external rubber skin to simulate part of the outer soft tissue of the skull (Synbone AG 2013). The base of the sphere has a central hole, through which ballistics gelatin can be introduced. Four spheres were utilized in this pilot study in two uniform thicknesses of 5mm and 7mm to allow for variation in thickness of skulls between individuals (Getz 1961: 221; Adeloye et al. 1975: 23; Lieberman 1996: 223; Lynnerup 2001: 45).

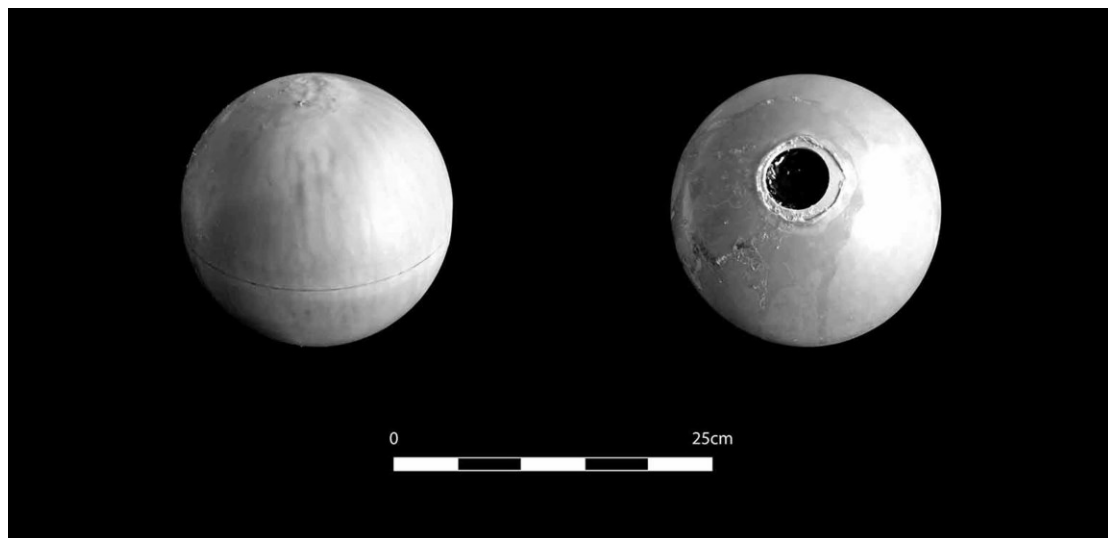


Figure 3: The assembled synthetic bone sphere.

Previous studies carried out on synthetic bone have demonstrated the need for the spheres to be filled for accurate fracture propagation (Carr et al. 2015: 506; Smith et al. 2015: 428). A 10% solution of ordnance level ballistics gelatin, which approximates the density of human soft tissue, was used to completely fill the spheres and act as the internal soft tissue of a living human skull (Fackler & Malinowski 1988: 219; Jussila 2004: 91; Carr et al. 2015: 506; Smith et al. 2015: 428).

Once constructed the skin-skull-brain spheres were placed on an elevated platform 108.0cm high, supported on a cork ring 3.1cm tall and 13.8cm in diameter. The hole in the sphere was placed facing down. A right-handed adult male, 30 years old, 193.0cm tall and 88.5kg carried out the strikes.

Two types of blows were used to investigate any variable fracture patterns produced by different areas of the club. Figure four shows the hand positions for the pommel blow and the double-handed blade strike. For the doubled handed strikes with the blade, the club was swung into the air and down onto the skin-skull-brain model, contacting at the end of the blade. The blows with the pommel end of the club, had the club drawn up and the pommel aimed at the skin-skull-brain model. The strikes with the pommel had a notable decrease in force.

Once struck, the resulting fractures were examined visually, photographed, and measured before and after the rubber skin, followed by the gelatin, were removed.



Figure 4: The hand position for the two types of blows. Left: The pommel strike. Right: The double-handed strike.

Results

The double-handed blade strikes produced relatively extensive depression fractures in both the 7mm and 5mm thick spheres. As seen in Table 2 and Figure 5, the impact site on the spheres created displaced pieces of bone. Differing numbers of radiating fractures also spread out from the area of impact, wrapping around the spheres. This is typical for extensive blunt force trauma (Oh 1983: 116; Lovell 1997: 150; Ortner 2003: 121; Calc & Rogers 2007: 519; Wedel and Galloway 2014: 129; Smith et al. 2015: 428). In the 5mm thick skull, the fractures became linked by circular tertiary fractures caused by further out-bending of the bone from the impact site, creating extensive displaced fragments of bone.

The pommel strikes formed a distinct variance on the predicted results. Both the 5mm and 7mm spheres had long linear fractures extending from the point of impact as listed in Table 2. These fractures ran in opposite directions from the area of initial impact (Figure 6).

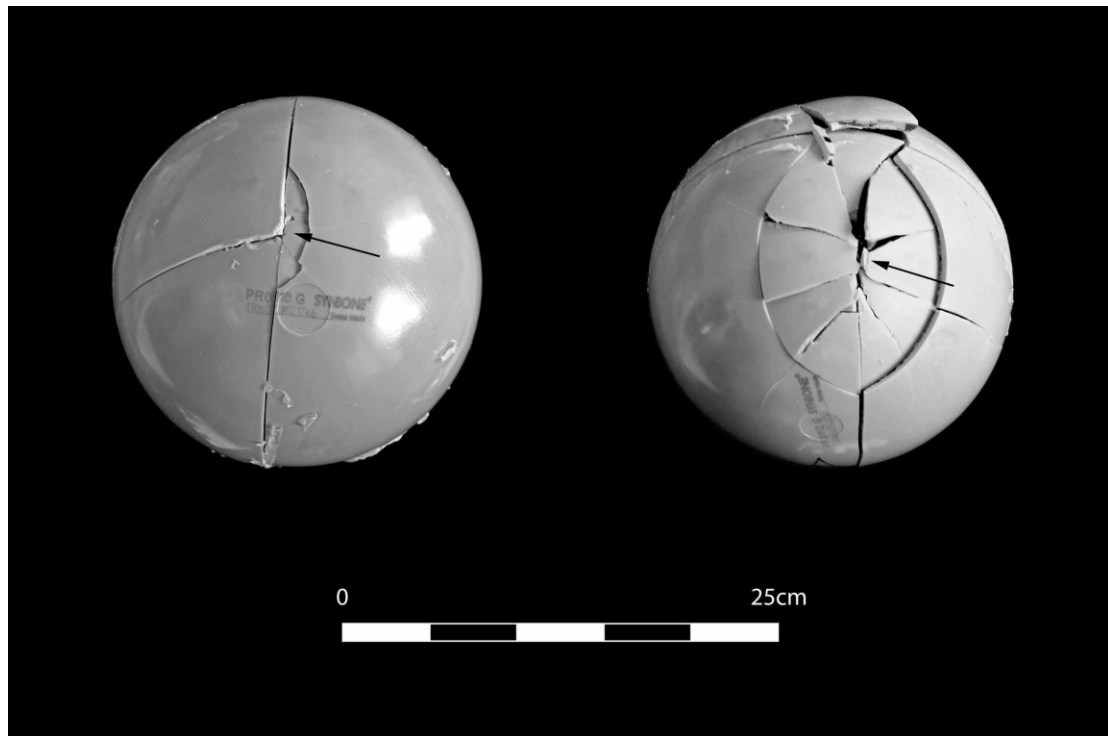


Figure 5: Impact site of the 7mm (left) and 5mm (right) spheres with central areas of depressed bone surrounded by radiating fractures. Arrows indicate the impact sites.

Table 2: Summary of fractures produced with the skin-skull-brain models. (Note that the size of depression fractures relates to the area of depressed bone created at the impact location and not bone displaced by intersecting radiating fractures).

Sphere Thickness	Type of Blow	Fracture Produced	Length	Width	Secondary/ Tertiary Fractures
7mm	Double-handed blade strike	Depression	51.0mm	37.0mm	Four large secondary radiating fracture lines.
5mm	Double-handed blade strike	Depression	111.0mm	80.0mm	Three large and many small secondary radiating fracture lines. Tertiary fracture causing the large area of displaced bone.
7mm	Pommel blow	Linear	32.0mm	<1mm	None
5mm	Pommel blow	Linear	40.0mm	<1mm	None

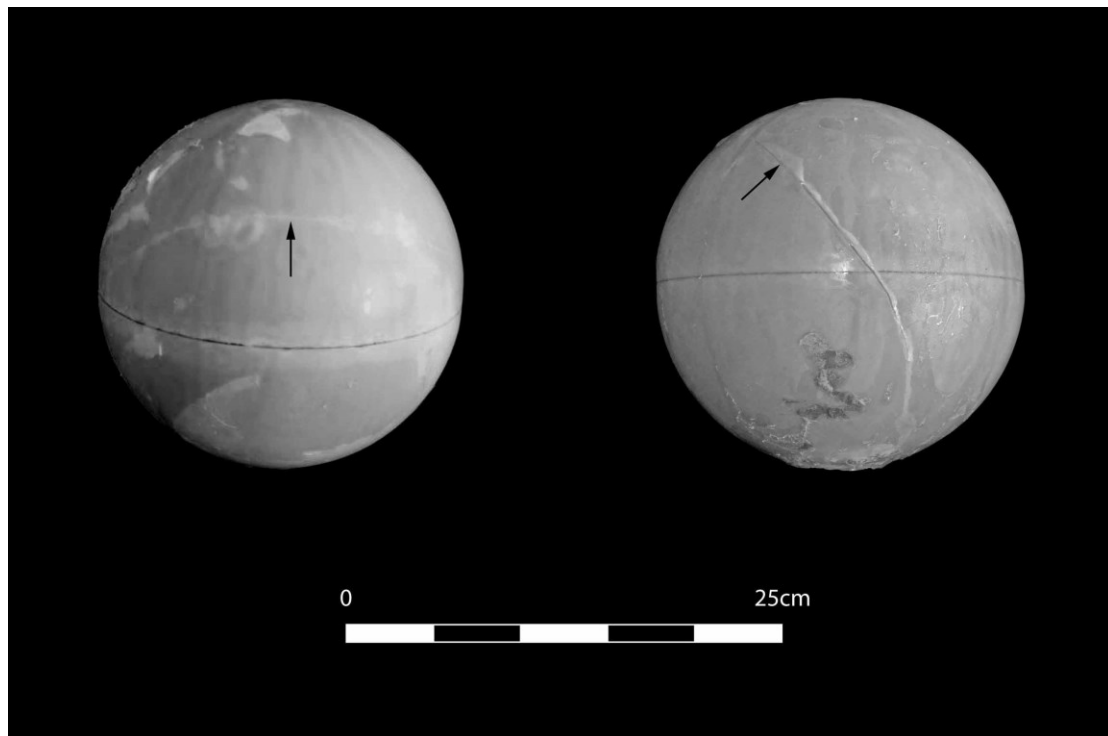


Figure 6: Linear fractures (indicated by arrows) produced by the pommel strikes on the 7mm (left) and 5mm (right) spheres.

Discussion

Synthetic Bone as an Accurate Medium

Synthetic bone 'skulls' are an emerging test medium in blunt force trauma studies (Thali et al. 2002a: 195, 2002b: 178; Carr et al. 2015: 505; Smith et al. 2015: 427). Smith et al.'s 2015 study demonstrated that there are some drawbacks, particularly at the microscopic level, in comparing synthetic polyurethane bone with living human tissue, however, this study confirms the ability of a skin-skull-brain model to provide clear and helpful results for archaeological testing of the macroscopic appearance of blunt force trauma.

The depression and linear fractures formed in the skin-skull-brain models display the characteristics of human skull fractures. The presence of internal beveling in the fractured synthetic bone fragments, as seen in Figure 7, along with the formation of radiating secondary and tertiary fractures appeared in the synthetic bone and are major diagnostic feature of blunt force trauma.

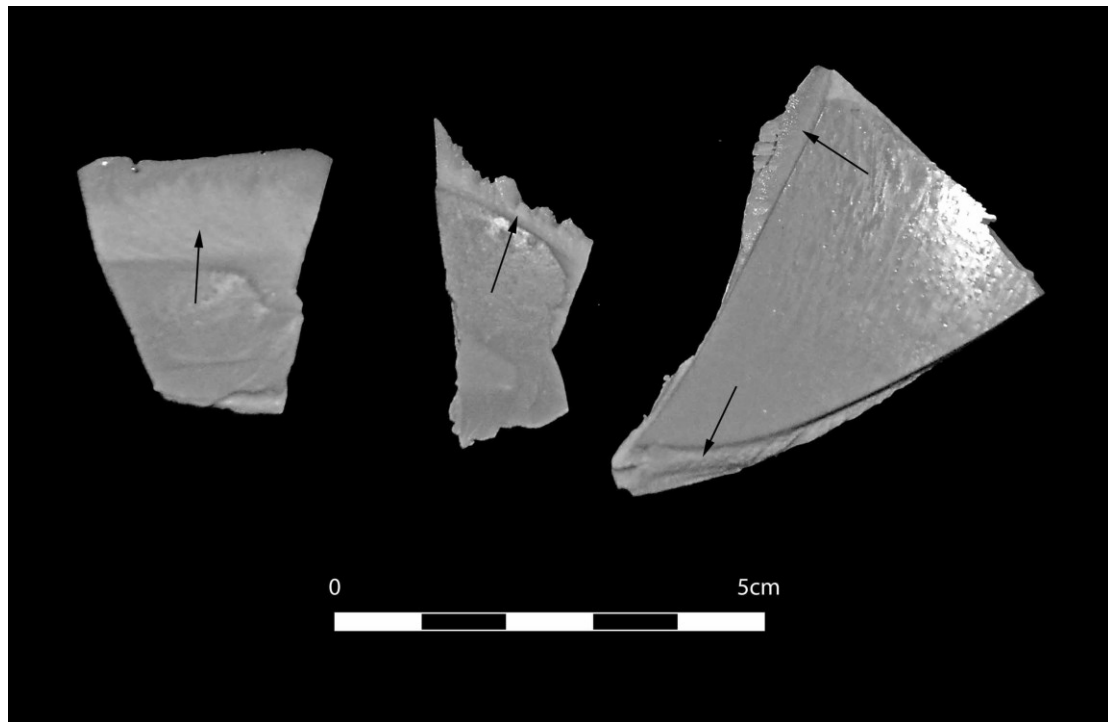


Figure 7: Displaced synthetic bone fragments from the double-handed strikes with beveled edges indicated by arrows.

Ultimately synthetic bone is able to adequately represent the biomechanical properties of frontal and parietal bones of living human crania (Thali et al. 2002a: 199, 2002b: 181; Carr et al. 2015: 506; Smith et al. 2015: 434), though the lack of cranial sutures and buttressing influences the fracture formation, and there is a stepped pattern to the beveled edges of the depression fractures which in actual human bone displays a smoother appearance.

Most importantly though, the skin-skull-brain model is able to reduce the error in experiments conducted with animal and cadaver substitutes. The specialized shape and cranial vault thickness of the human skull cannot be accurately compared with animal substitutes (Corey et al. 2001: 104; Byard et al. 2007: 31; Wedel & Galloway 2014: 38; Smith et al. 2015: 427). Experiments with cadavers also raise ethical, and legal questions, which prevent their use in many archaeological studies (Corey et al. 2001: 99; Thali et al. 2002b: 178; Smith et al. 2015: 427). Synthetic bone models remove ethical and legal issues, are easily obtainable, are able to biomechanically respond closer to real human skull material than animal substitutes and provide a standardized model without specimen variation (Thali et al. 2002b: 178; Carr et al. 2015: 506; Smith et al. 2015: 427).

Archaeological Comparisons – Double-Handed Strikes

The depression fractures formed by the double-handed blade strikes to the skin-skull-brain models have significant resemblance to examples of diagnosed intentional blunt force trauma in the Neolithic osteological record. The fracture morphology, shape of displaced fragments and the beveled fracture edges produced in both spheres match very closely with trauma hypothetically linked to wooden club weapons (Teschler-Nicola et al. 1996; Schulting and Wysocki 2005: 125; Teschler-Nicola 2012: 108). This

experimental study successfully demonstrates the accuracy of this summation, most notably with the remarkable match found in the 7mm thick sphere.

The fractures present on the 7mm sphere bear remarkable similarity to injuries in Individual 3, a 35-40 year old male from the Neolithic Austrian site of Asparn/Schletz (Teschler-Nicola et al. 1996; Teschler-Nicola 2012: 107). As seen in Figure 8, both skulls have a long thin depression site near the top of the skull, with several radiating fractures. The impact sites on both also have one straight and one slightly curved border. This is a remarkable match between the archaeological record and the experimental results.

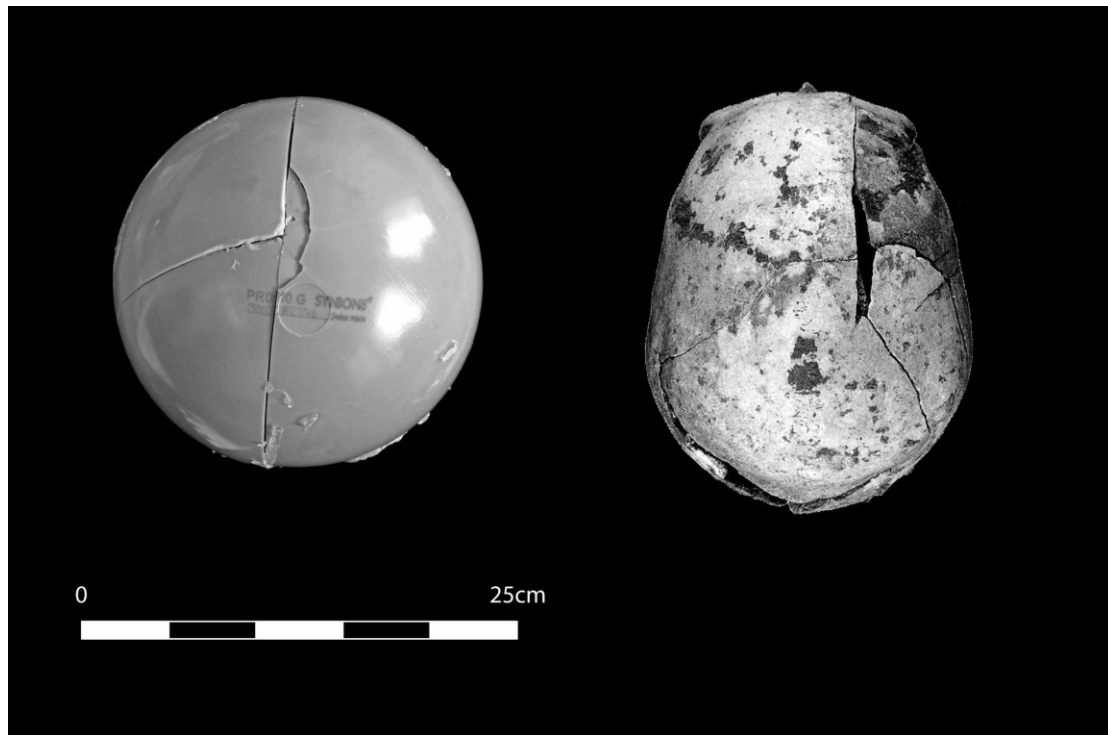


Figure 8: Comparison between the depression fracture on the 7mm sphere and the fractures found on Individual 3, a 35-40 year old male, at the site of Asparn/Schultz (skull not to scale).

The stark similarities between the experimental models and the archaeological specimens provide a potential link between many of the cases of cranial trauma noted in the archaeological record and wooden clubs used as weapons of violence. Asparn/Schletz represents a single event massacre site (Teschler-Nicola 2012: 108; Meyer et al. 2015: 11217) and the clearly lethal nature of the tested wooden club is in line with a motivation to kill. It must now be established if this same type of weapon could also produced some of the healed trauma found in Neolithic population studies. The use of the same weapon would require an interpretation that considered why some survived attacks with such a lethal tool, while the use of a different weapon type could suggest a different type of interpersonal violence. A study investigating some of these questions is currently in progress.

The Anomalous Linear Fractures

The strikes with the pommel end of the club deviated greatly from the original hypothesis that the small, rounded surface and more controlled swing would produce small, non-lethal depression fractures. Instead, a distinct linear fracture formed, radiating out from the point of contact. The lower impact energy that causes linear fractures can be the result of intentional violence or accidental trauma (Ta'ala et al. 2006: 996; Sahoo et al. 2013; Freeman et al. 2014: 64; Wedel & Galloway 2014: 137). The ambiguity of the mechanism of injury commonly leads to the exclusion of these fractures in archaeological analysis of violence (Lovell 1997: 154; Ortner 2003: 121; Schulting & Wysocki 2005: 110).

There is a possibility that the formation of these fractures is due to the synthetic bone's biomechanical properties, an issue that requires further experimental studies; however, the presence of documented cases of linear fracture formation from intentional injury (Ta'ala et al. 2006: 996; Sahoo et al. 2013; Wedel & Galloway 2014: 137), and their striking conditions lend credence to a clear possibility that intentional trauma can produce the lower impact energy that forms linear fracture injuries. The hand placement for the pommel-led strikes greatly limited the swing distance and energy of the attack. The decrease in energy is the most likely reason for linear fracture propagation (Lovell 1997: 150; Ortner 2003: 121). These results warrant further investigation as it could have great influence on the current practice in archaeological trauma studies.

Wooden Clubs as Weapons of Violence

Though the Thames Beater is an individual artifact from England, it does provide a good example of wooden clubs that could be crafted during the European Neolithic and beyond and is representative of this general category of implement. It is not suggested that this specific implement was responsible for any cranial trauma observed in the archaeological record, but that the class of implement it represents certainly could have been.

The strong correlation between the experimental injuries inflicted by the Thames Beater and the archaeological cases from Asparn/Schletz lends potential support to the theories of the use of wooden clubs as short-range weapons of interpersonal violence in Neolithic Europe. With the recent rise in population and individual site studies presented in the literature, there is increasing information about violence in the Neolithic period, with extensive variation in the interpretation of the context (Keeley 1996; Orschiedt et al. 2003; Golitko & Keeley 2007: 332; Mercer & Healy 2008: 145; Boulestin et al. 2009; Lorkiewicz 2011: 432; Schulting & Fibiger 2012: 2; Wahl & Trautmann 2012:85; Martin & Harrod 2014: 116).

It is likely that not all violent events of the Neolithic occurred for the same reasons, and no single explanation will provide a blanket context for all violence in the period (Chenal et al. 2015: 1329). A better understanding of the weapons being used as the massacre sites like Talheim, Schöneck-Kilianstädten, and Asparn/Schletz (Teschler-Nicola 2012: 108; Wahl & Trautmann 2012: 85; Meyer et al. 2015: 11217) and those being used for the more low level endemic violence appearing in larger population studies (Schulting & Wysocki 2005: 107; Lawrence 2006: 53; Smith & Brickley 2007: 25; McKinley 2008: 477; Ahlström & Molnar 2012: 17; Schulting 2012: 223; Schulting & Fibiger 2012; Fibiger et al. 2013: 190) could increase our

understanding of how these seemingly different types of violent events were occurring alongside each other.

Conclusion

This study demonstrates a probable link between a potentially widespread type of Neolithic tool and examples of cranial blunt force trauma from the archaeological record, demonstrating wooden clubs possible connection to trauma in at least one individual from Asparn/Schletz. The results of this paper are the primary step towards showing comparability between a particular weapon and blunt force injury in the Neolithic. Further research is currently being undertaken by the authors to test other potential weapon-tools and explore the possibility of differentiating Neolithic blunt force weapons based on cranial fracture patterns.

This is the first time an experimental model has been used to accurately examine blunt force trauma from a prehistoric site. The methodology established in this paper can be applied to studies of the possible weapon tools of the period to establish variations in the methods being used for violence. This should provide a better understanding of the varying contexts and mechanisms of violence in the Neolithic, and thus create a better understanding of social interactions across Western and Central Europe.

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